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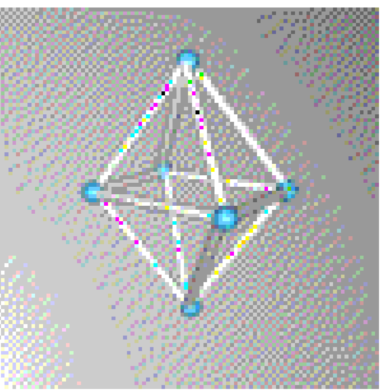
Cross Layer Issues in Sensor Networks: *A Line In The Sand*



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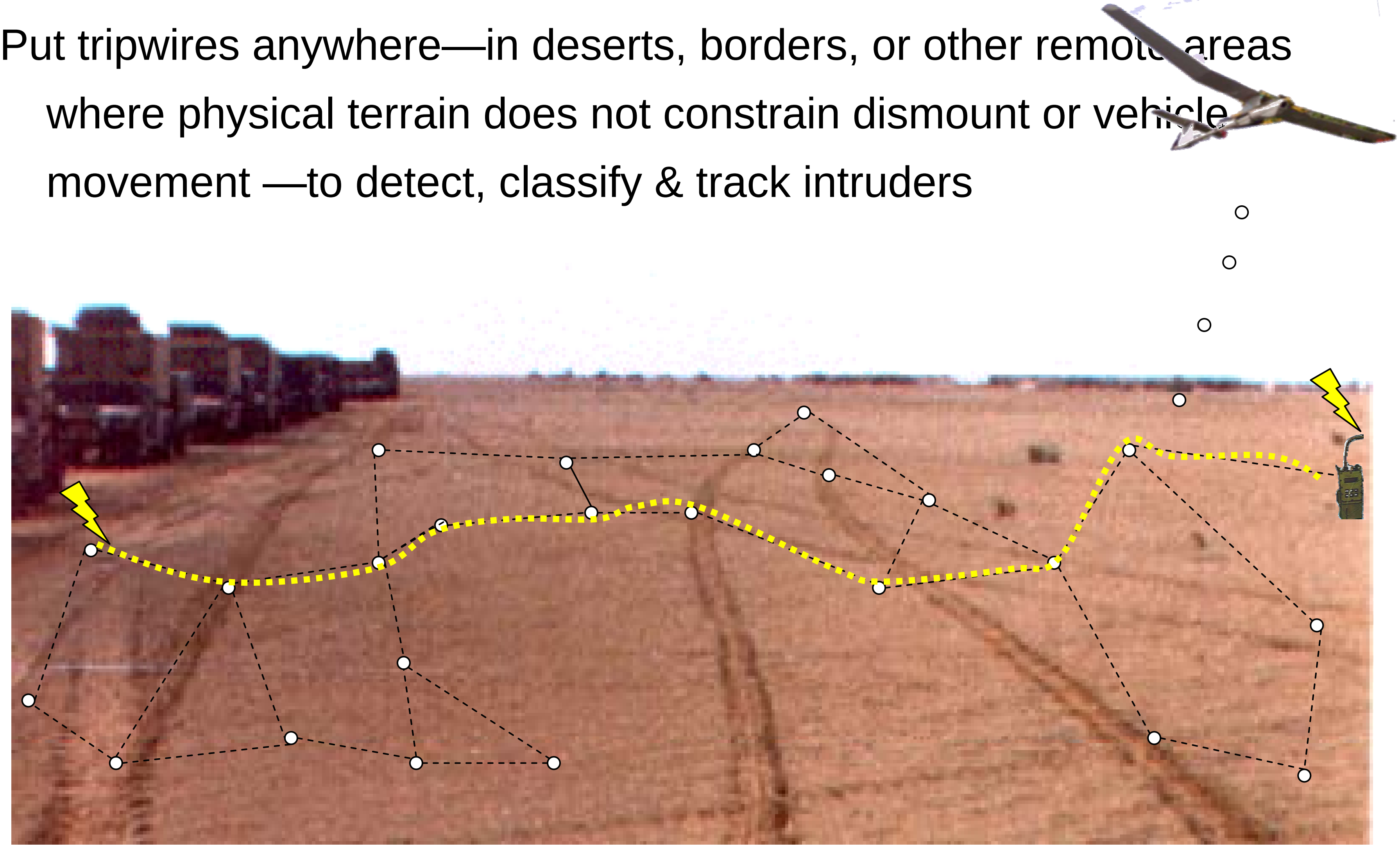
Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

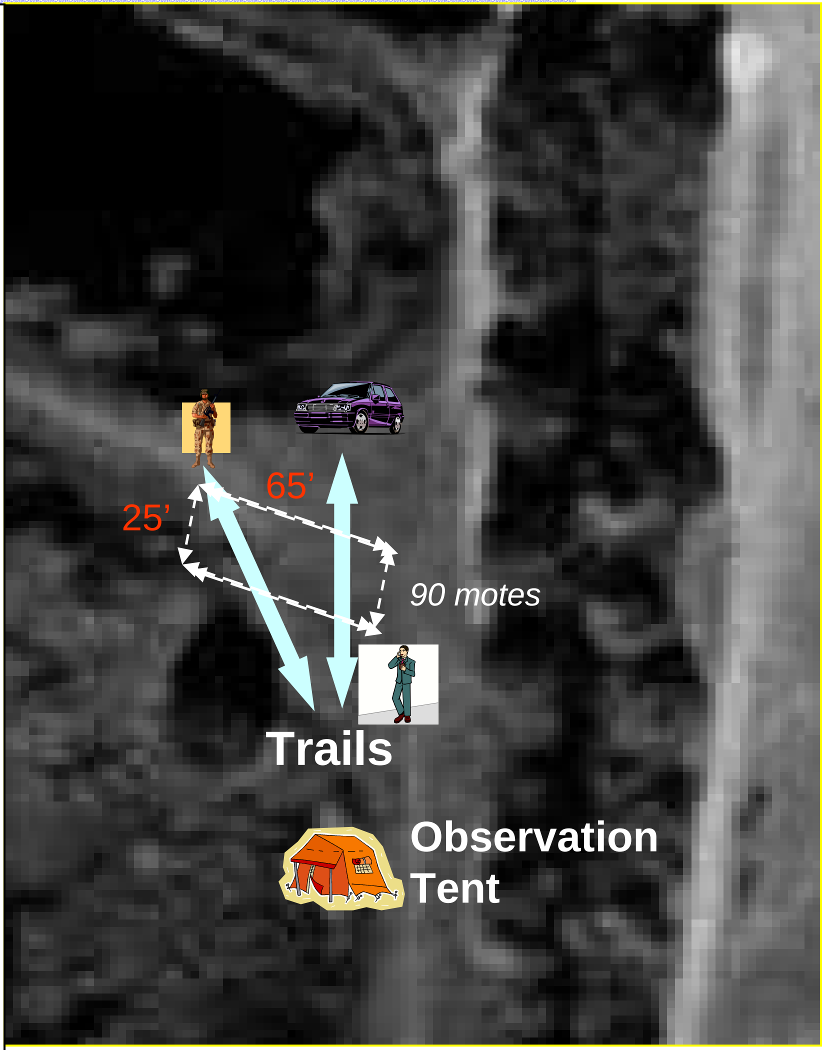
Concept of operations

Put tripwires anywhere—in deserts, borders, or other remote areas where physical terrain does not constrain dismount or vehicle movement —to detect, classify & track intruders



Field experiment: Layout & scenarios

- Hand-placed 90 nodes w/ magnetometer & micro-power impulse radar sensors
- System *detects* each intruder & *classifies* it as one or none of known intruder types
- System *tracks* intruder as it moves & *visualizes* location/type remotely

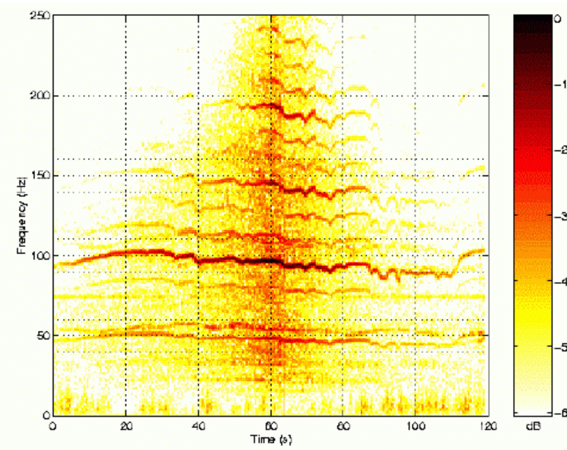


- Soldier carrying "gun"
  - walks/runs across line on trails
  - with another soldier on different trail/times
- Car
  - runs across line on trails at 5-20mph
- Civilian
  - walks across line in zig-zag pattern

Concept of system design

Traditional approach: centralized, resource-rich

- each sensor classifies intruders independently
- technique: each intruder type has unique, sophisticated *time-frequency signature*



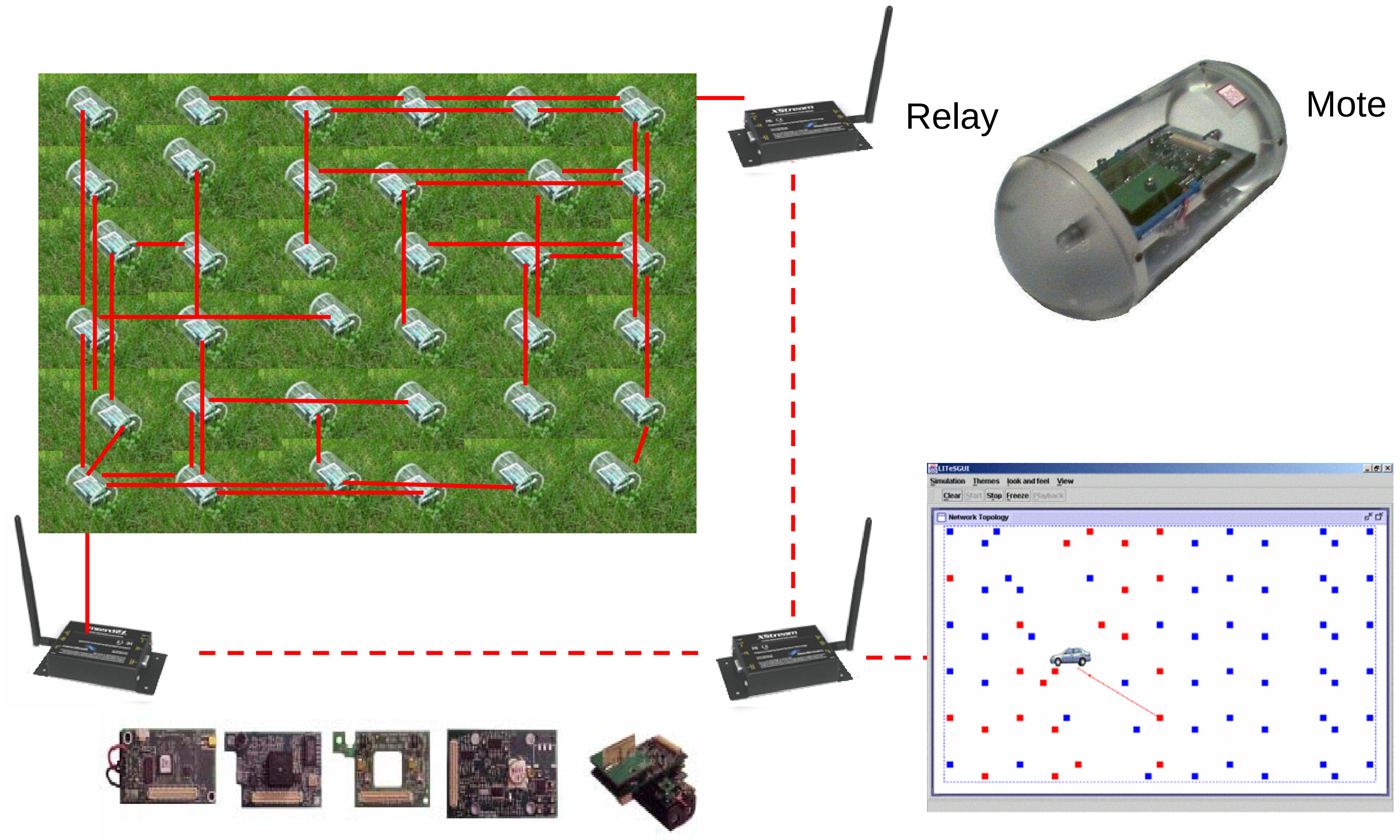
The *A Line in the Sand* approach: distributed, dense, resource-poor

- multiple sensors coordinate, each with multiple modalities
- sample concept: each intruder type has unique *influence field*

Implications of our approach

- focus on network middleware & its impact on application

System setup and devices



System challenges vs. application requirements

Requirements:

- accurate classification & tracking (<2% false positives&negatives, <3m)
- bounded latency (<15 sec)

Challenge: Unreliable network of mote nodes & links

- low capacity, time varying links
- contention unavoidable for large, bursty traffic
- limited energy
- hostile environment: heat, humidity, tall grass
- misbehaving nodes: yield both false negatives & positives

System architecture:

- application layer:
  - at mote tier: detection, generation of local reports
  - at higher tier: classification & tracking
- network layer: PHY, MAC, routing, timesync, …

Cross layer issues: network service design

Resource constraints in our embedded platform substantially affected service design

Correctness issues were discovered when system scaled (from ~10 to ~100 nodes); led to:

1. redesign of networks protocols
   - to accommodate unreliability, nonuniformity of network
2. tuning of network parameters
   - for helping achieve accuracy of application
3. tuning application to accommodate network behavior
   - for managing despite network quality

Lesson learned:

- simulations insufficient for discovering/predicting issues
- easy for application to be operating at close to capacity

Redesign of network protocols to deal with scaling

Large event traffic bursts compromised several network services

Time-sync

- tree-based solution failed to scale: due to partitions

$\Rightarrow$ Max-based multipath scheme had to be implemented

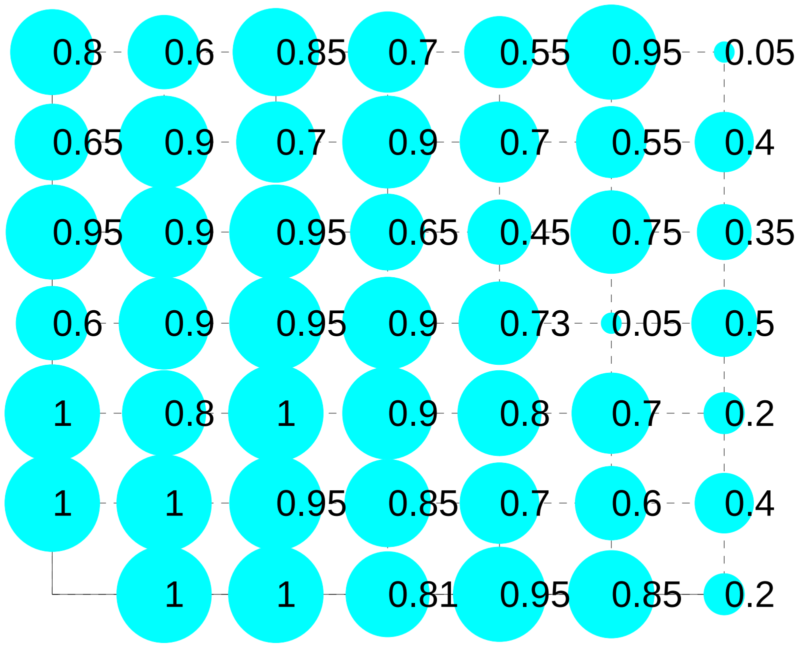
Routing

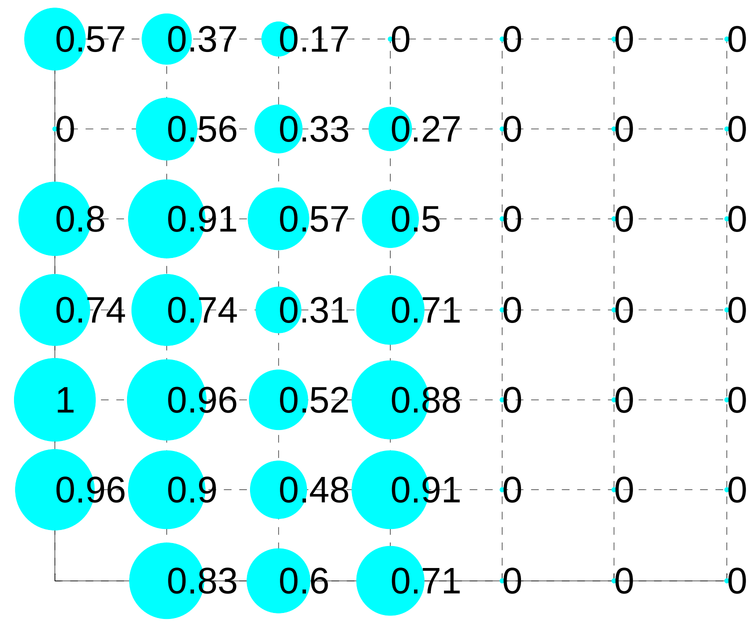
- reliability was too low: link estimation during traffic bursts is hard
- but reliability was necessary to guarantee:
  - separation of influence field sizes (for classification)
  - shape preservation of influence field (for tracking)
- and application required minimum jitter

$\Rightarrow$ Grid routing + Reliable link layer had to be implemented

(but implicit ack vs. explicit ack selected only by experiments)

Grid Routing vs. Mint Routing under bursty traffic





Grid Routing

Greater reliability

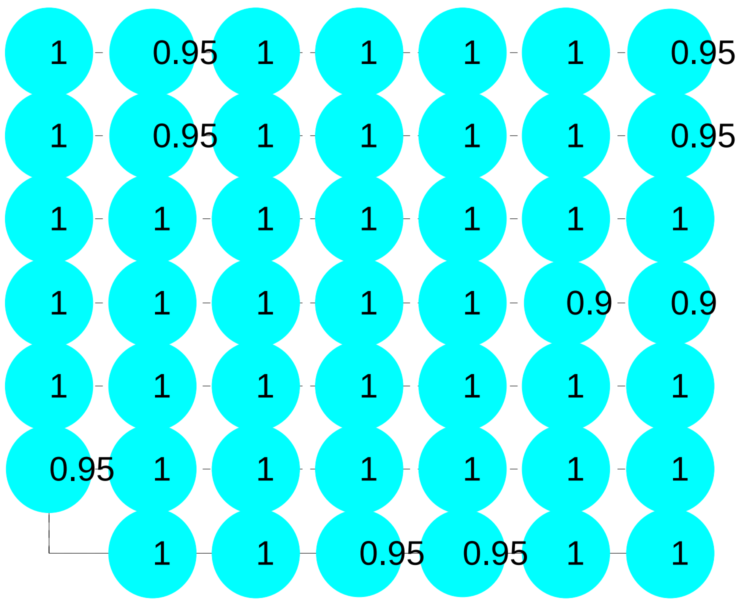
Uniform across the network

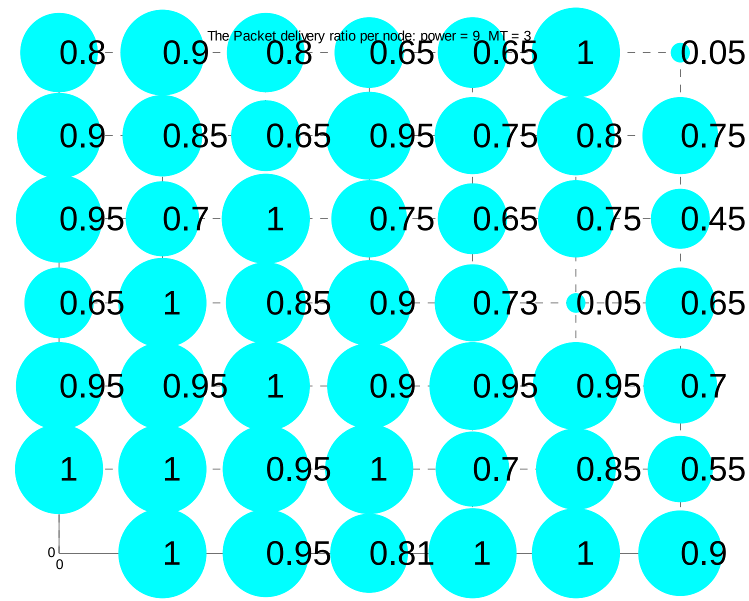
Mint Routing

Lesser reliability

Nonuniform

Implicit vs. Explicit acks





Grid Routing & Implicit Ack
with up to 2 retransmissions

Average of 98 %

Grid Routing & Explicit Ack
with up to 2 retransmissions

Average of 81%

Co-design of network protocol parameters

- Several parameters had to be tuned to help meet application requirements:
  - transmission power level at PHY layer
    - when high: decreases reliability, more contention
    - when low: more hops, decreases reliability and increases delay
  - MAC layer random back-off
    - tune along with power level to reduce collisions
    - large back-off gives more reliability, but tradeoff with delay
  - number of re-transmissions
    - increases reliability only if spaced apart
    - increases latency as well

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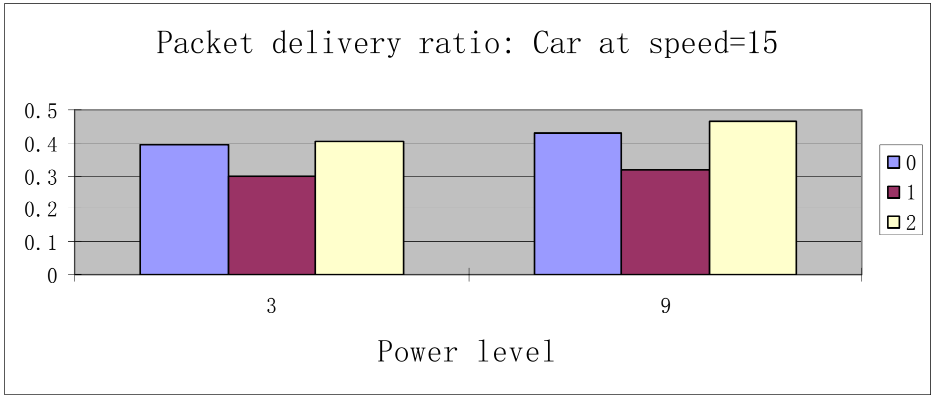
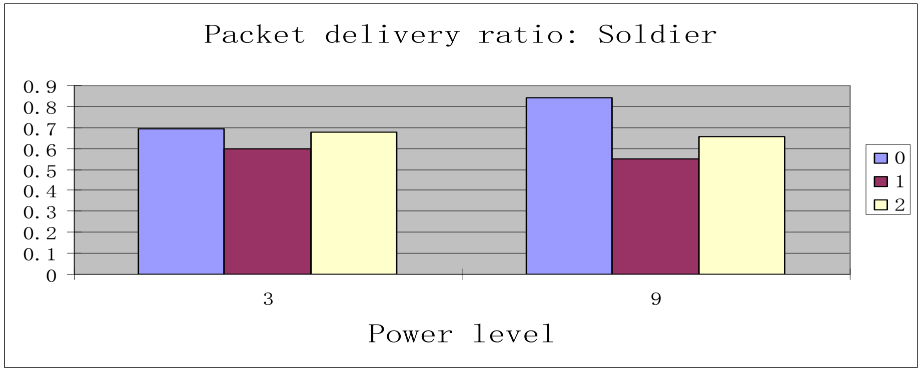
Statistics on packet delivery ratio

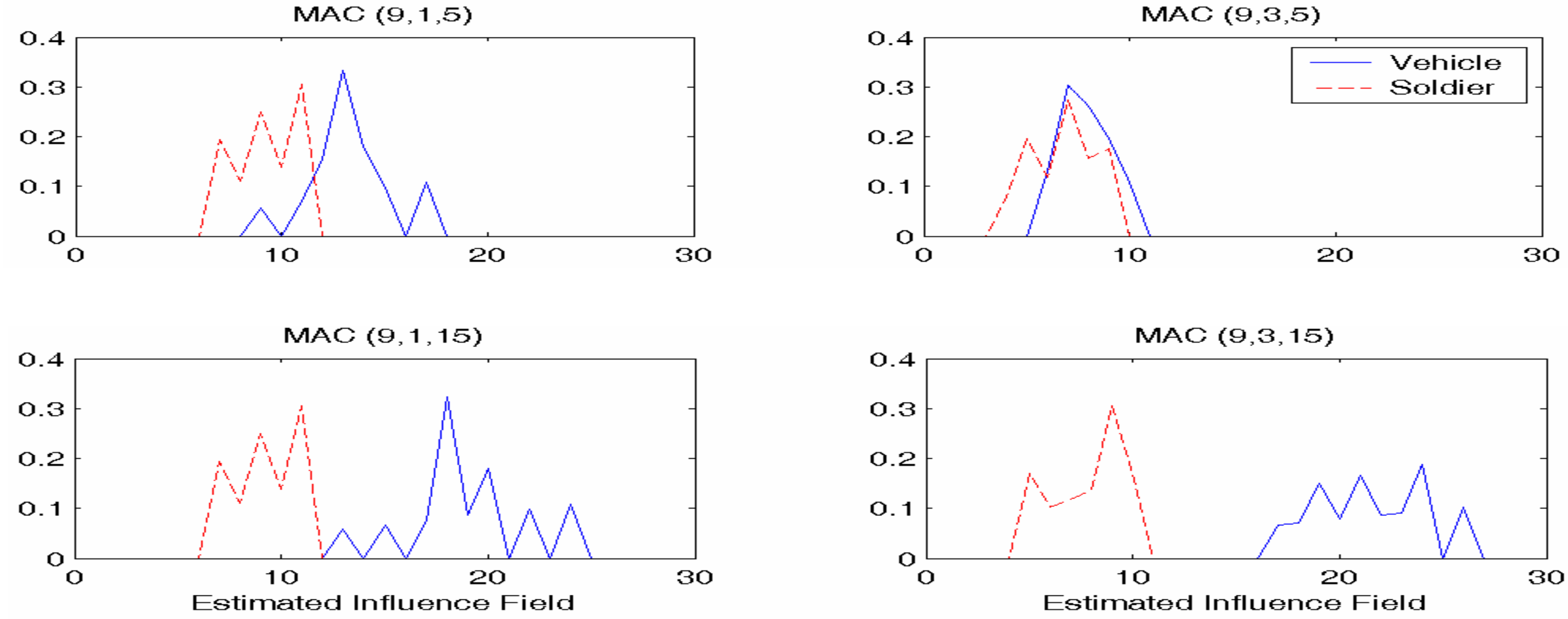




Observations:

- delivery ratio increases as the power level increases
- for car, decreases when the retransmission goes from 1 to 2, & increases from 1 to 3
- for soldier, decreases from 1 to 3

Delivery ratio critical for accurate classification



- MAC (power, number of transmissions, delay at classifier)
- Power level = 9, number of transmissions = 3, gives best accuracy
- Delay = 13 seconds

Co-design of application

Application design also dependent on network quality

0. Window of spatial aggregation of events at higher tier depended on network jitter

1. For influence fields where network reliability cannot guarantee separation, need to stretch interval for calculation of influence field: *Temporal Aggregation*

2. Since unreliability increases with distance from relay, higher tier had to compensate by adjusting number of received messages based on distance: *Spatial Reconstruction*

3. Generation of reports from the mote application made probabilistic to compensate for network effects: *Probabilistic Reporting*

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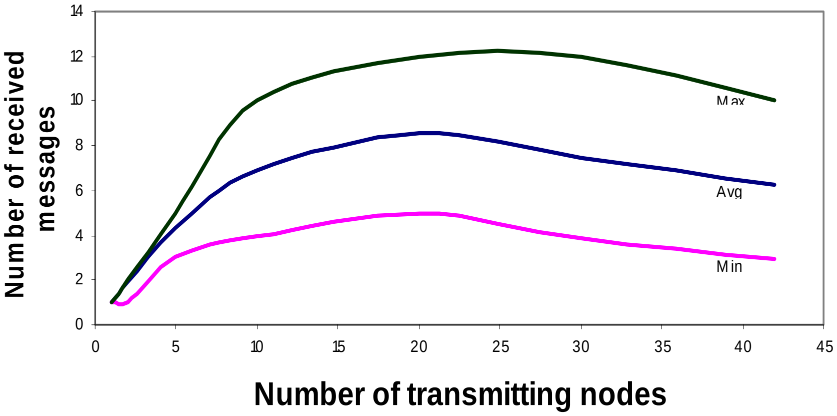
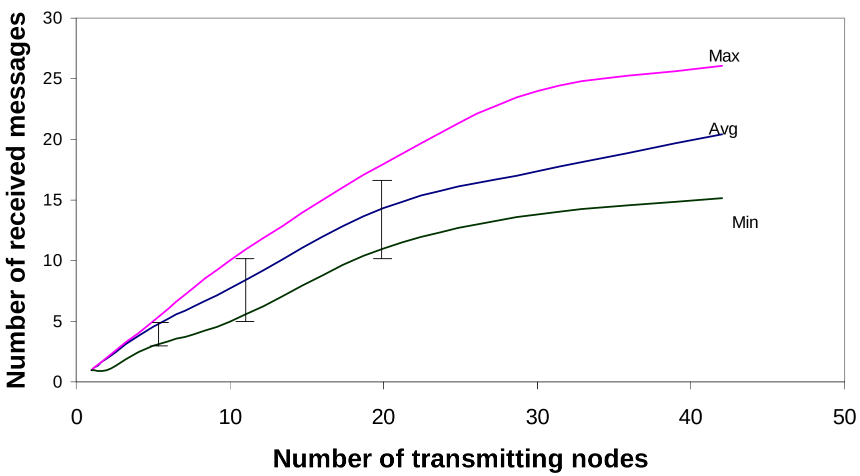
Probabilistic reporting

- Without probabilistic reporting



- With probabilistic reporting



With P (Reporting) = 0.5

Future work

- Team is leading the fielding of *Echelon* this year
  - application to protect 10km by .5km area
  - 10,000 Tier 1 nodes, <5 hop sections
  - 300 Tier 2 nodes, 30 hop network

- Space and time varying conditions across sections of network

$\Rightarrow$ *Echelon* is to autonomic/adaptive wrt cross layer interactions

  - scale in the presence of cyclic dependencies across layers
  - stability across layers will be key